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July 15, 1965

Search for C Violation in η(958 MeV) and η(549 MeV) Decays*

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There is now much interest in the possibility of C (charge conjugation) noninvariance in strong or electromagnetic interactions, which is due to the existence of C-violating but parity-conserving interactions.[1,2] The violation is a few percent at most for the strong interactions and can be maximal for the electromagnetic interactions. Such C-violating effects may be found by looking for (1) C-violating decay modes of neutral mesons[3-6] or (2) asymmetries between π^+ and π^- in the three-particle decay modes of these same mesons.[3,4,7] We have looked for such decay modes and asymmetries arising from η(958) and η(549)[8] produced in the reaction $K^-p \rightarrow \Lambda\eta(958)$ with subsequent decay $\eta(958) \rightarrow \eta(549)\,\pi^+\pi^-$. No definite evidence for such C-violating effects is observed, although their presence cannot be ruled out. The smallness of the decay of η(549) and η(958) to $\pi^0 e^+ e^-$ is of particular interest. The branching fractions are <0.007 and <0.013, respectively; 0.01 and 0.02, respectively, might be expected.

The η(958) mesons are produced in the reaction $K^-p \rightarrow \Lambda\eta(958)$. About 700 000 pictures of 2.1-, 2.45-, 2.55-, 2.63-, and 2.70-BeV/c K^- mesons incident upon the 72-inch hydrogen bubble chamber have been used. Essentially all of the V-plus-4- or 6-pronged events have been measured, as well as

about two-thirds of the V-plus-2-pronged events. All events in which the mass, M_Λ, of the system recoiling against the Λ is in a wide band about 958 MeV [$0.80 \leq M_\Lambda^2 \leq 1.04$ (BeV)^2] had previously been selected and fitted to the final states $\Lambda\pi^+\pi^-\gamma$ and $\Lambda\eta\pi^+\pi^-$ in addition to the usual hypotheses, as reported previously.[9] A subset of these events was selected for final processing in the search for the possible C-violating decay modes, $\eta(549 \text{ or } 958) \rightarrow \pi^0 e^+ e^-$ or $(\pi^+\pi^-)_{T=0} e^+ e^-$, or $\eta(958) \rightarrow \eta(549) e^+ e^-$. For this search, only events with low momentum transfer to the Λ, $\Delta^2_{p,\Lambda} < 0.5$ (BeV)^2, were used. The subset was chosen by calculating the missing mass opposite all visible particles, using the electron mass in place of the pion mass for all possible $e^\pm$ combinations among the charged tracks at the production vertex. Those events having a missing mass near $0, \pi^0$, or $\eta(549)$ [$-0.05 \leq MM^2 \leq 0.4$ (BeV)^2] were retained. The original measurements were selected from the measurement-library tapes and reprocessed through geometry and kinematics (PACKAGE) with all the appropriate hypotheses, including electrons. Fits or missing-mass calculations were tried to the following reactions:

$$
\begin{aligned}
K^- p &\rightarrow \Lambda\pi^+\pi^- \text{ (+ neutrals)} \\
&\rightarrow \Lambda e^+ e^- \text{ (+ neutrals)} \\
&\rightarrow \Lambda 2\pi^+ 2\pi^- \text{ (+ neutrals)} \\
&\rightarrow \Lambda\pi^+\pi^- e^+ e^- \text{ (+ neutrals)} \\
&\rightarrow \Lambda 3\pi^+ 3\pi^- \\
&\rightarrow \Lambda 2\pi^+ 2\pi^- e^+ e^-;
\end{aligned}
$$

where intermediate $\eta(549)$ and (or) Σ^0 production and decay were included as required. Of approximately 75 000 original V-plus-2- or 4-pronged measurements, approximately 16 000 had $0.80 \leq M_\Lambda^2 \leq 1.04$ (BeV)^2; the final selected subsample used here has about 2500 events.[11] Many electron hypotheses were

fitted satisfactorily. Essentially all those hypotheses having a momentum less than about 200 MeV/c for either electron were ruled out on the basis of the visible ionization. No distinction between pions and electrons was possible at higher momenta. We obtained many ambiguous fits between $\Lambda\pi^+\pi^0\pi^-$, $\Lambda\pi^+\pi^-\gamma$, $\Lambda\pi^0e^+e^-$, and $\Lambda e^+e^-\gamma$ in particular, which presumably are really $\Lambda 3\pi$ or $\Lambda 2\pi\gamma$.[12]

The candidates for the various decay modes are given in Table I. The second column gives the number of events that fit best to the decay listed in the first column, the third column gives the number of unambiguous cases, and the fourth column gives other candidates.[13] The fifth and sixth columns give, respectively, the observed number of definite candidates, and the lowest (three-standard-deviation) upper limit consistent with columns 2 through 4. The seventh column gives the number of such events expected on the basis of the crude theoretical estimates[3,4] that have been made (see footnote 14 for details). Finally, the last column gives the upper limit to the branching fractions. Clearly the data are consistent with C invariance, although the observed upper limits are not inconsistent with the theoretical expectations. However, the 0 ± 1 $\eta(549)$ and 0 ± 3 $\eta(958) \rightarrow \pi^0e^+e^-$, taken at face value, are less than the expected 3 and 15, respectively.[15]

No statistically meaningful asymmetries between π^+ and π^- in the decay of $\eta(958) \rightarrow \eta(549)\ \pi^+\pi^-$ or $\pi^-\pi^-\gamma$ are observed. The relevant numbers are presented in Table II.[16,17] Clearly a sample an order of magnitude larger would be needed before one could expect to see any real effect, if present.

In summary, a search for C-violating decay modes and asymmetries in $\eta(549)$ and $\eta(958)$ decays has been made. No C-violating effects are observed, although the sensitivity of the measurement is such that even a maximal violation in electromagnetism cannot be ruled out. However, as noted above, the

$\pi^0 e^+ e^-$ decays may be suppressed relative to current crude estimates. Such a suppression might be due to the operation of some other approximate quantum number,[18] or the fact that the C-violating coupling does not violate isospin.[19] It is hoped that the data given in this letter will be of use in limiting the range of possible theoretical speculations regarding C violation.

We wish to acknowledge the support and cooperation of the many members of the Alvarez group and the Bevatron staff. We especially thank Prof. Luis W. Alvarez for his support and encouragement, and for his hospitality to one of us (GRK). We acknowledge with thanks helpful discussions with Professors E. C. Fowler, S. L. Glashow, T. D. Lee, A. Pais, and W. J. Willis.

Table I. C-violating decay modes for $\eta(549)$ and $\eta(958)$.[a]

Mode	Events: Best fit	Events: Unambiguous	Events: Other[b]	Observed events: Definite	Observed events: Upper limit	Expected events[c]	Observed branching fraction[d]
$\eta(549) \to \pi^0 e^+ e^-$	0	0	3	0	3	$0.03 \times (89\ \eta_C \pi^+ \pi^-) = 3$	<0.007
$\to \pi^+ \pi^- e^+ e^-$	0	0	---	0	3	$0.002 \times (89\ \eta_C \pi^+ \pi^-) = 0$	<0.007
$\eta(958) \to \pi^0 e^+ e^-$	3 ± 5[e]	0	$\frac{0 \pm 1}{0.33}$	0	9	$0.1 \times (152\ \pi^+ \pi^- \gamma) = 15$	<0.013
$\to \eta\, e^+ e^-$ η_N	$\frac{-4 \pm 3}{0.7}$[e]	$\frac{0}{0.7}$	---	0	7	$0.01 \times (152\ \pi^+ \pi^- \gamma) = 2$	<0.011
$\to \eta\, e^+ e^-$ η_C	$\frac{0}{0.3}$	$\frac{0}{0.3}$	---				
$\to \pi^+ \pi^- e^+ e^-$	2	2	---	2[f]	6	$0.01 \times (152\ \pi^+ \pi^- \gamma) = 2$[f]	<0.006
$\eta(958) \to \rho^0 \pi^0$	---	---	7 ± 6[e]	0	25	$\approx 0.01\ (\frac{172\ \eta_N \pi^+ \pi^-}{0.36 \pm 0.05})$[g] $= 5$	<0.04
$\to \omega^0 \pi^0$	---	---	29 ± 9[e]	0	56		<0.08

[a] As determined from events with $0.89 \leq M^2_\Lambda \leq 0.95$ (BeV)^2 and $\Delta^2_{p;\Lambda} \leq 0.5$ (BeV)^2; also see footnote 8.

[b] See footnote 13.

[c] See footnote 14.

[d] Upper limit (column 6)/[η(549 or 958) → all modes]; see reference 9 for all other branching fractions.

[e] Number of events above background.

[f] The number of events expected is given for internal conversion or C-violating, T=0, $\pi^+\pi^-$ decay each separately. Note that the 2 events observed are consistent with being due to $\rho\gamma$ internal conversion.

[g] The denominator is the branching fraction for $\eta(958) \to \eta_N \pi^+ \pi^-$ (see reference 9), and the 0.01 represents C violation in strong interactions. These upper limits have been discussed previously (see reference 3).

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Table II. Asymmetries.

Mode	Events	$\frac{N_+ - N_-}{N_+ + N_-}$ [a]	Possible magnitude
$\eta(549) \rightarrow 3\pi$	$0.8 \times 89\ \eta_C$	---[b]	≤ 0.05[c]
$\eta(958) \rightarrow \eta\pi^+\pi^-$	$172\ \eta_N\pi^+\pi^-$	$-0.04 \pm .08$	$<<0.01$[d]
	$89\ \eta_C\pi^+\pi^-$	---[b]	
$\eta(958) \rightarrow \pi^+\pi^-\gamma$	152 (all)	$+0.07 \pm .08$[e]	
	86 (near ρ)[f]	$+0.05 \pm .11$[e]	<0.10[g]

[a] $N_\pm$ is the number with $\cos\theta_{\pm\gamma} > 0$; the error is $(N_+ + N_-)^{-1/2}$ for small asymmetry.

[b] Not attempted because of ambiguity in identification of the $\eta \rightarrow 3\pi$ triplet among the five pions $(2\pi^+ \pi^0 2\pi^-)$.

[c] See footnote 4.

[d] Strong decay.

[e] See footnote 16.

[f] Subsample with $0.4 < M^2(\pi^+\pi^-) < 0.7$ (BeV)^2.

[g] See footnote 17.

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FOOTNOTES AND REFERENCES

* Work done under the auspices of the U. S. Atomic Energy Commission.

1. T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965).

2. J. Prentki and M. Veltman, Phys. Letters 15, 88 (1965).

3. S. L. Glashow and C. M. Sommerfield, Phys. Rev. Letters 15, 78 (1965).

4. J. Bernstein, G. Feinberg, and T. D. Lee, "Possible C, T Noninvariance in the Electromagnetic Interaction," (to be published in Phys. Rev.); G. Feinberg, "Some Consequences of the Proposed C and T Violations in the Electromagnetic Interactions," (Columbia University preprint).

5. F. A. Behrends, Phys. Letters 16, 178 (1965); Y. Fujii and G. Marx, Phys. Letters 17, 75 (1965); S. Barshay, Phys. Letters 17, 78 (1965); J. Prentki and M. Veltman, "C Violation in Strong Interactions," (CERN preprint).

6. A negative result on the decay $\eta(549\ \text{MeV}) \rightarrow \pi^0 e^+ e^-$ has been reported by L. R. Price and F. S. Crawford, Jr., Phys. Rev. Letters 15, 123 (1965).

7. T. D. Lee, "Remarks on Possible C-Noninvariant Effects in the 3π Decay of η^0 and ω^0," (to be published in Phys. Rev.); M. Nauenberg, "The $\eta \rightarrow \pi^+\pi^0\pi^-$ Decay with C-Violation," (Stanford University preprint); J. Prentki and M. Veltman, Phys. Letters 17, 77 (1965).

8. We denote the η at 549 MeV and the $\eta 2\pi$ resonance at 958 MeV as $\eta(549)$ and $\eta(958)$, respectively, because both appear to be $TJ^{PG} = 00^{-+}$ mesons (see references 9 and 10). Also we denote the decays $\eta(549) \rightarrow \pi^+\pi^0\pi^-$ and $\pi^+\pi^-\gamma$ as η_C and $\eta(549) \rightarrow$ all neutrals as η_N. We use $[\eta(549) \rightarrow \pi^+\pi^-\gamma]/\eta_C \approx 0.2$, $[\eta(549) \rightarrow \pi^+\pi^0\pi^-]/\eta_C \approx 0.8$, and $\eta_C/[\eta(549) \rightarrow \text{all modes}] \approx 0.3$. [See A. H. Rosenfeld, et al., Rev. Mod. Phys. 36, 977 (1964).]

9. G. R. Kalbfleisch, O. I. Dahl, and A. Rittenberg, Phys. Rev. Letters 13, 349A (1964).

10. G. R. Kalbfleisch et al., Phys. Rev. Letters 12, 527 (1964); M. Goldberg et al., Phys. Rev. Letters 12, 546 (1964); M. Goldberg et al., Phys. Rev. Letters 13, 249 (1964); P. M. Dauber et al., Phys. Rev. Letters 13, 449 (1964).

11. In addition, approximately 500 V-plus-0-, 2-, and 4-pronged events plus a Dalitz pair were measured as V-plus-2-, 4-, and 6-pronged events, respectively, and processed similarly. If a Dalitz pair had been noted in the original scanning, the event had been recorded as though the Dalitz pair were absent, and then a "flag" had been set to indicate it. The C-violating decay modes involving an $e^{\pm}$ pair would not give "Dalitz-like" pairs in general; as expected, none of these events yielded any candidates.

12. Those events that fit best as $\Lambda\eta_N e^+e$, $\Lambda\pi^0 e^+e^-$, or $\Lambda e^+e^-\gamma$ were all examined on the scanning table for interactions, delta rays, and bremsstrahlen on the charged tracks in order to find any definite electron candidates. None were found.

13. The 3 $\eta(549) \rightarrow \pi^0 e^+e^-$ candidates are events fitting best as η_C but fitting $\pi^0 e^+e^-$ with a probability greater than 0.1 of the η_C fit. The $(0 \pm 1)/0.33$ $\eta(958) \rightarrow \pi^0 e^+e^-$ candidates are those in which either of the electrons had a momentum less than 200 MeV/c in the laboratory. The number 0.33 is the estimated fraction of such decays from a "fake" calculation (using the $\pi^0 e^+e^-$ matrix element given in reference 4). We thank Prof. W. J. Willis for the use of his program. The $\eta(958) \rightarrow \rho^0\pi^0$ candidates may be incorrectly identified $\rho^0\gamma$ events; also, the $\eta(958) \rightarrow \omega^0\pi^0$ candidates may be (C-conserving) $\omega^0\gamma$ or $\eta_C\pi^0\pi^0$ events, since these three hypotheses are experimentally indistinguishable.

14. The numbers of events expected are based on a possible maximal violation of C in electromagnetism. The C-violating decay modes proceed with order α^2 and can be compared with other α^2 decay rates [$\eta(549 \text{ or } 958) \rightarrow 2\gamma$, for example]. The $\eta(549) \rightarrow 2\gamma$ rate is known to be approximately the same as η_C (see footnote 8). The $\eta(958) \rightarrow 2\gamma$ mode has not yet been observed but is expected to be about 0.1 of the $\rho\gamma$ mode, or about 0.02 of the total rate. See L. M. Brown and H. Faier, Phys. Rev. Letters 13, 73 (1964); S. K. Kundu and D. C. Peaslee, Nuovo Cimento 36, 277 (1965); and R. H. Dalitz and D. G. Sutherland, "X^0 - η Mixing and Some Radiative Meson-Decay Processes," (University of Oxford, preprint). The $\eta(549) \rightarrow \pi^0 e^+ e^-$ decay is suppressed by SU_3 + CPT invariance [see N. Cabbibo, Phys. Rev. Letters 14, 965 (1965), theorem 9]. The $\eta(958) \rightarrow \pi^0 e^+ e^-$ decay is not suppressed by SU_3. Thus $\eta(549) \rightarrow \pi^0 e^+ e^-$ can proceed via mixing from the $\eta(958)$ at 0.01 of the total rate (see reference 4) as well as by a comparable amount due to SU_3-breaking interactions. The $\eta(958) \rightarrow \pi^0 e^+ e^-$ proceeds unsuppressed at about the 2γ rate (see references 3 and 4) plus some contribution from SU_3 breaking interactions introduced by mixing from $\eta(549)$. The $\eta(958) \rightarrow \eta(549) e^+ e^-$ is suppressed by phase space (references 3 and 4). The $(\pi^+\pi^-)_{T=0} e^+ e^-$ modes are, apart from any SU_3 suppressions, at a rate about that of internal conversion, which is of order $\alpha(\pi^+\pi^-\gamma \text{ rate})$. We note that all C-violating modes (of order α^2) can proceed at order α^4 without C violation.

15. The previously reported result of 0 ± 1 $\eta(549) \rightarrow \pi^0 e^+ e^-$ candidates with an upper limit of 4 (see reference 6) is also less than the expectation of $0.03 \times [219\ \eta(549) \rightarrow \pi^+\pi^0\pi^-] \simeq 7$ events.

16. The asymmetry can also be described by an asymmetry parameter α. The decay of a $TJ^{PG} = 00^{-+}$ particle into $\pi^+\pi^-\gamma$ gives an intensity distribution,

$$I = N^* \sin^2\theta \, (1 + \alpha \cos\theta + \beta \cos^2\theta),$$

for p-wave, C-conserving and d-wave, C-violating amplitudes (see reference 4). The N^*, α, and β contain the momentum dependencies, including any resonant Breit-Wigner terms. The asymmetry parameter α is obtained from the moments of $\cos^n\theta$,

$$\alpha = \frac{8 \langle\cos\theta\rangle}{3 - 7 \langle\cos^2\theta\rangle}.$$

All 152 events give $\alpha = 0.55 \pm 0.42$ and the 86 events near the ρ give $\alpha = 0.04 \pm 0.24$.

17. The value of 0.10 for the $\pi^+\pi^-\gamma$ asymmetry parameter can be obtained for a p- to d-wave amplitude ratio equal to one at the peak of the ρ resonance. Since the ρ amplitude dominates $\eta(958) \rightarrow \pi^+\pi^-\gamma$, a considerably smaller d-wave amplitude might be expected.

18. An example is the A-parity of J. B. Bronzan and F. E. Low, Phys. Rev. Letters 12, 522 (1964). The decay $\pi^0 e^+ e^-$ can proceed through the internal emission and absorption of a virtual photon, so that $\pi^0 e^+ e^-$ has A = -1. Kundu and Peaslee (see footnote 14) believe that the $\eta(958)$ has A = +1, so that $\eta(958) \rightarrow \pi^0 e^+ e^-$ and that part of $\eta(549) \rightarrow \pi^0 e^+ e^-$ arising from the singlet-octet mixing would be suppressed. The $\eta(549) \rightarrow \pi^0 e^+ e^-$ [and $\eta(958)$ from the "mixing"] can still have a component arising from SU_3-violating interactions.

19. The possibility that the C-violating interactions conserve isospin has been considered by Prentki and Veltman (see reference 5) and by T. D. Lee, "Classification of All C-Noninvariant Electromagnetic Interactions and the Possible Existence of a Charged, but C = 1, Particle," (Columbia University preprint).